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Comparison of ISO 6336 and AGMA 2001 Load Capacity Ratings for Wind Turbine Gears-Sensitivity Study for Profile Shift, Helix Angle, and Normal Pressure Angle

By: Robert Errichello

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100 BUSHBUCK ROAD
TOWNSEND MT 59644

INTRODUCTION

The AGMA/AWEA Wind Turbine Committee is considering guidelines for gear rating in accordance with ISO 6336 and AGMA 2001 in AGMA/AWEA 6006-AXX [1]. However, many investigators [2,3,4,5,6,7,8] have shown ISO 6336 and AGMA 2001 ratings can differ significantly. These differences must be addressed to develop reliable guidelines.

Variations between ISO 6336 and AGMA 2001 ratings are due to differences between numerous parameters that influence gear rating and differences in engineering models.

ISO 6336 and AGMA 2001 use similar analytical models for load capacity based on durability (macropitting resistance). However, the work reported here shows ISO 6336 and AGMA 2001 have different sensitivities to profile shift, helix angle, and normal pressure angle.

ISO 6336 and AGMA 2001 use fundamentally different models for load capacity based on bending strength (bending fatigue resistance). Comparison studies [2,3,4,7,8] have shown ISO 6336 and AGMA 2001 give different trends for the influence of profile shift on bending strength. ISO 6336 is relatively insensitive to profile shift, whereas AGMA 2001 shows profile shift has a strong effect.

Several studies [2,3,7,8] have shown ISO 6336 is relatively insensitive to helix angle, whereas AGMA 2001 is very sensitive.

OBJECTIVE

This study compares ISO 6336 and AGMA 2001 ratings with focus on sensitivity of both rating methods to the geometric variables of profile shift, helix angle, and normal pressure angle.

SCOPE

Spur, low-contact-ratio helical gears, and conventional helical gears were analyzed for durability and bending strength. Scuffing resistance was not considered because ISO 6336 offers no method.

RATING STANDARDS

All gearsets were rated in accordance with ISO 6336 [9,10,11,12] and AGMA 2001 [13].

SOFTWARE

All gearsets were rated using the ISO 6336 computer program [14] and AGMA218 [15]. Gear and hob geometries were calculated with GEARCALC [16].

RATING PARAMETERS

To obtain rating comparisons independent of derating factors, input data for the ISO 6336 and AGMA218 computer programs were prepared with the same derating factors for application, load distribution, and dynamics. Additionally, the same gear and hob geometry was used for both programs. Generating rack shift coefficients were used in the ISO 6336 program to obtain correct root diameters.

ISO 6336 input data were as follows:

x_1 prescribed
Hob geometry, x_2, Δs_{n1}, Δs_{n2}, d_{a1}, d_{a2}, u_{s1}, and u_{s2} from GEARCALC
$x_{g1} = x_1 - \Delta s_{n1}/(2 * \tan\alpha_n)$
$x_{g2} = x_2 - \Delta s_{n2}/(2 * \tan\alpha_n)$
$K_A = 1.0$
$K_{H\beta} = 1.3$
$K_{H\alpha}$ = calculated by ISO 6336
$K_{F\beta}$ = calculated by ISO 6336
$K_{F\alpha}$ = calculated by ISO 6336
K_V = calculated by ISO 6336

AGMA218 input data were as follows:

x_1 prescribed
Hob geometry, x_2, Δs_{n1}, Δs_{n2}, d_{a1}, d_{a2}, u_{s1}, and u_{s2} from GEARCALC
$C_a = K_V * K_{H\beta} * K_{H\alpha}$ for durability (K_V, $K_{H\beta}$, $K_{H\alpha}$ from ISO 6336)
$C_a = K_V * K_{F\beta} * K_{F\alpha}$ for strength (K_V, $K_{F\beta}$, $K_{F\alpha}$ from ISO 6336)
$C_m = 1.0$
$C_V = 1.0$

Rating procedure was as follows:

The ISO 6336 program was run first, and derating factors calculated by ISO 6336 were used to calculate C_a for input to AGMA218.

For both programs, input power was varied until calculated stresses equaled baseline stresses corresponding to baseline values for geometric parameters as follows:

$x_1 = x_{1min}$ for profile shift sensitivity
$\beta = 0°$ for helix angle sensitivity
$\alpha = 15°$ for pressure angle sensitivity

Results were expressed as relative load capacity normalized by the baseline load corresponding to baseline values for geometric parameters $x_1 = x_{1min}$, $\beta = 0°$, $\alpha = 15°$.

INFLUENCE OF PROFILE SHIFT

Figures 1 and 2 show the results of analyzing spur gear examples 5 through 10 from Castellani [2] with the ISO 6336 [14] and AGMA218 [15] computer programs. All gear geometry was held constant except profile shift and tip diameters. Profile shift varied over the range:

$$0.1642 \le x1 \le 1.0$$

To isolate the effects of profile shift on gear durability, factor K_{Hx} is defined as follows:

$$K_{Hx} = \frac{I}{I_{x1\min}}$$

Where:

K_{Hx} = load capacity relative to x1 = 0.1642

I = gear durability geometry factor

$I_{x1\min}$ = gear durability geometry factor for x1 = 0.1642

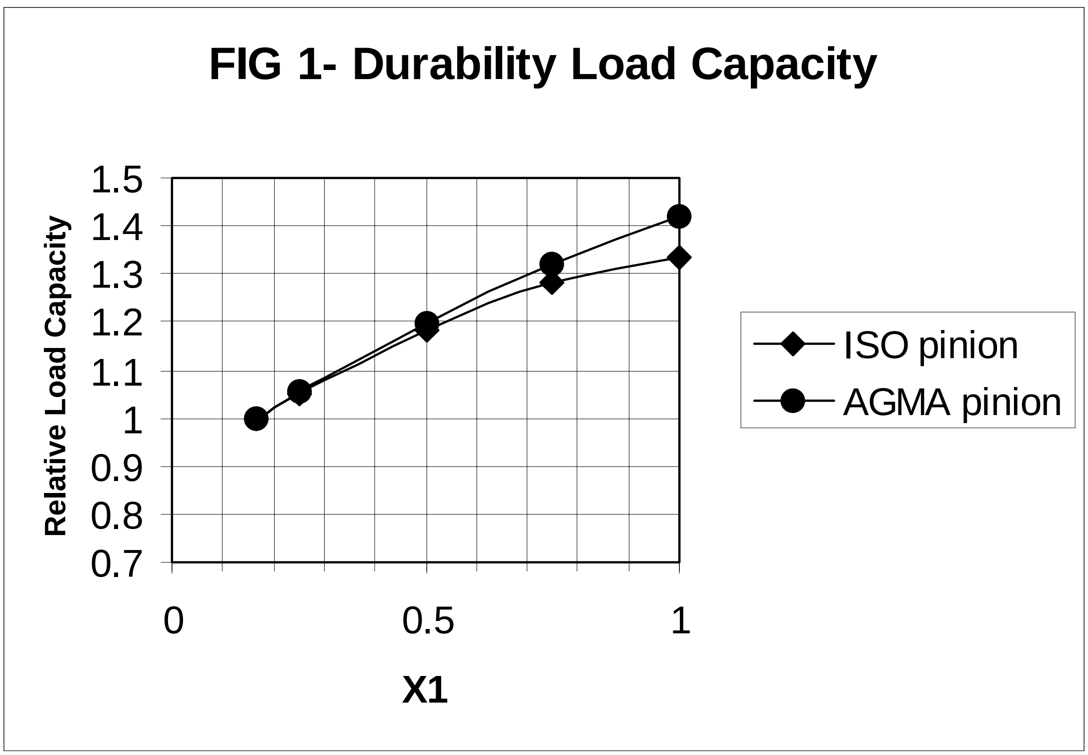

Figure 1 shows AGMA 2001 and ISO 6336 durability load capacities have similar response to varying profile shift. At x1 = 1.0 the AGMA load capacity is K_{HX} = 1.42 (42% increase in durability due to profile shift). In contrast, the ISO load capacity shows a 33% increase in durability.

To isolate the effects of profile shift on gear strength, factor K_x [4] is defined as follows:

$$K_x = \frac{J}{J_{x1\min}}$$

Where:

$K_x = \text{load capacity relative to x1} = 0.1642$

$J = \text{gear strength geometry factor}$

$J_{x1\min} = \text{gear strength geometry factor for x1} = 0.1642$

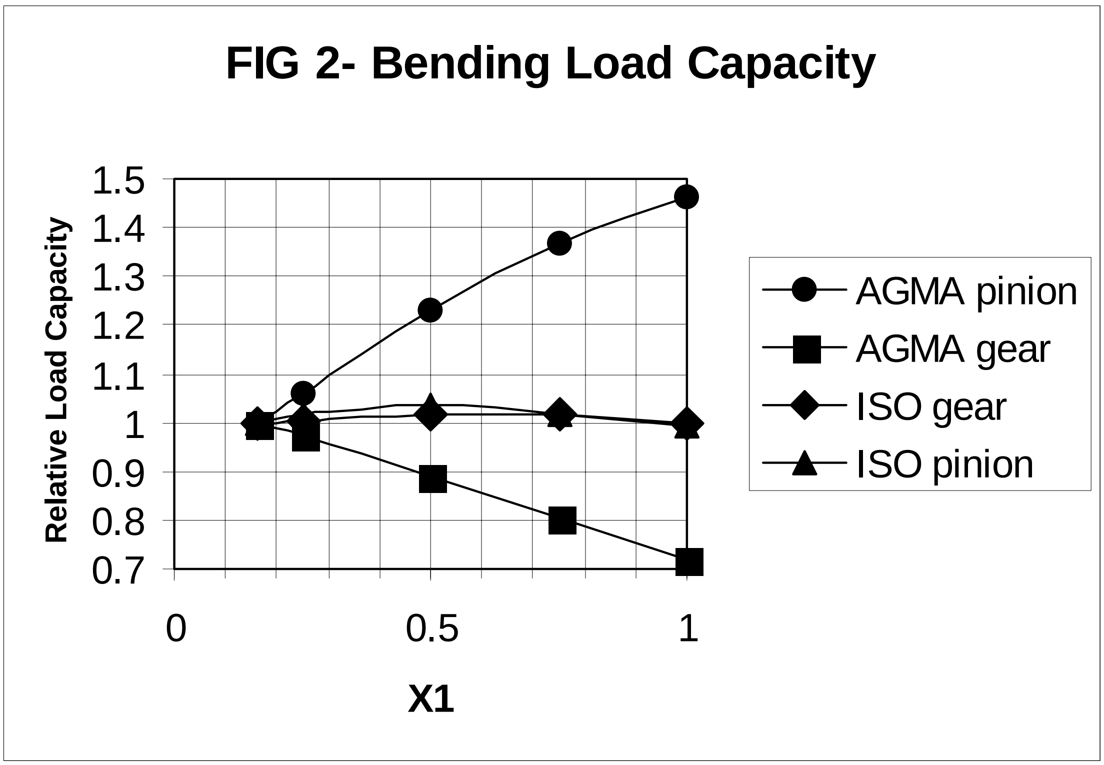

Figure 2 shows AGMA 2001 bending strength is very sensitive to profile shift whereas ISO 6336 has negligible response. At x1 = 1.0 the AGMA load capacity is K_X = 1.46 (46% increase in strength due to profile shift). In contrast, the ISO load capacity shows a 1% <u>decrease</u> in strength (K_x = 0.99). Similar divergence is obtained for the gear (AGMA K_x = 0.72, ISO K_x = 0.99 for x1 = 1.0).

Insensitivity of ISO 6336 to profile shift, and the trend for decreasing bending strength for x1 > 0.5, are implausible and inconsistent with experience.

Divergence between ISO 6336 and AGMA 2001 durability and bending strength with increasing profile shift is important because most wind turbine gears are designed with profile shift.

INFLUENCE OF HELIX ANGLE

Figures 3 and 4 show the results of analyzing example 7 from LaBath [7] with the ISO 6336 [14] and AGMA218 [15] computer programs. Center distance was held constant by holding transverse module constant and varying normal module. Helix angle varied over the range:

$$0 \leq \beta \leq 30^\circ$$

FIG 3- Durability Load Capacity

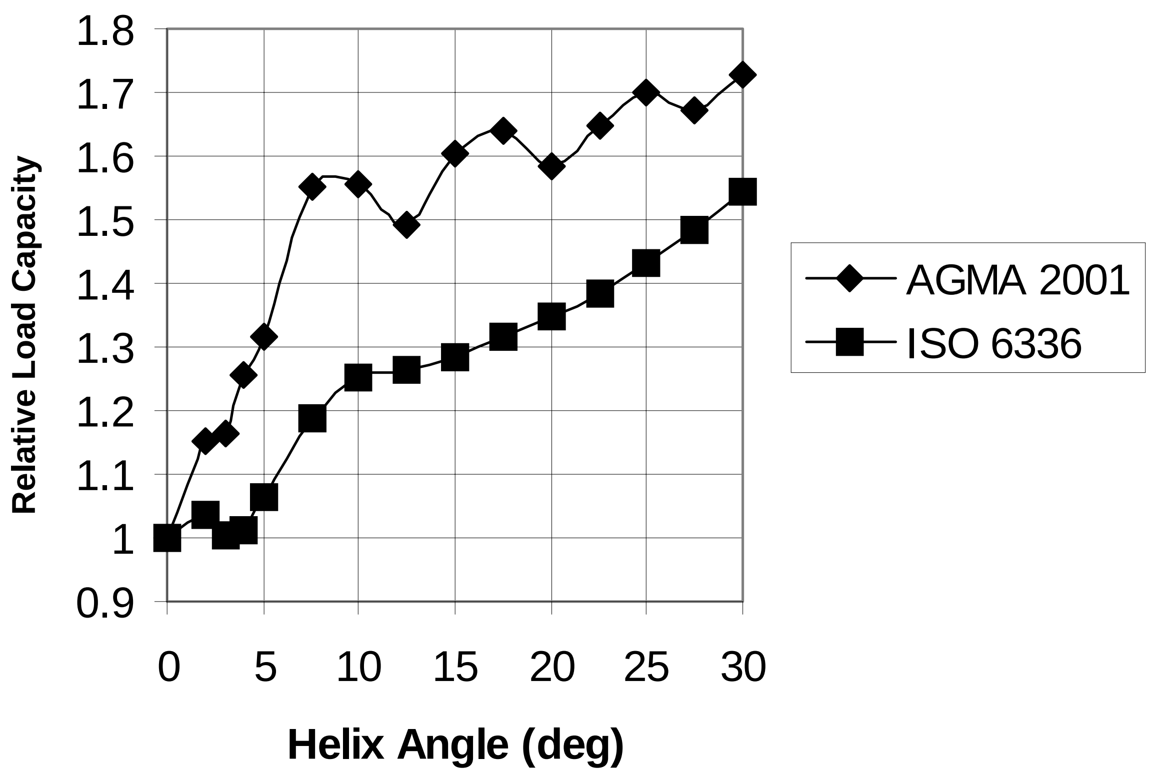

Figure 3 shows AGMA 2001 durability load capacity is very sensitive to helix angle whereas ISO 6336 has a significantly smaller response. For example, at $\beta = 7.5^\circ$ AGMA load capacity increases 55% compared to a spur gear. In contrast, ISO load capacity shows only a 19% increase.

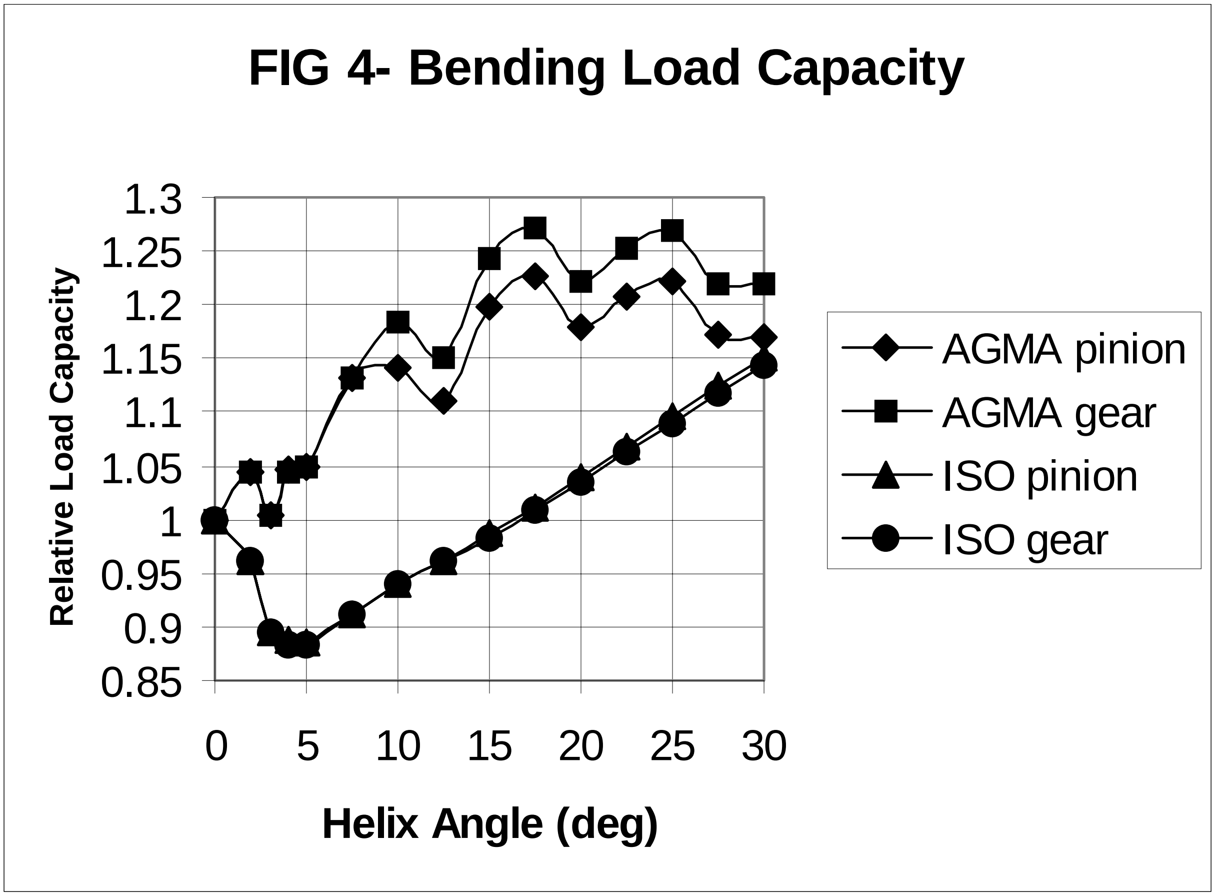

Figure 4 shows AGMA 2001 bending load capacity is very sensitive to helix angle whereas ISO 6336 has a significantly smaller response for most helix angles. Furthermore, ISO 6336 has an opposite trend for small helix angles. For example, at $\beta = 7.5°$ AGMA load capacity increases 13% compared to a spur gear. In contrast, ISO load capacity shows a 9% <u>decrease</u>. Similarly, at $\beta = 17.5°$ AGMA load capacity increases 23% whereas ISO load capacity shows only a 1% increase. For $\beta < 17°$, ISO 6336 calculates less load capacity for helical gears than spur gears.

The trend for decreasing load capacity for small helix angles, and the low load capacity relative to a spur gear for $\beta < 17°$, make ISO 6336 ratings implausible and inconsistent with experience.

INFLUENCE OF NORMAL PRESSURE ANGLE

Figures 5 and 6 show the results of analyzing example A from Hosel [3] with the ISO 6336 [14] and AGMA218 [15] computer programs. All gear geometry was held constant except normal pressure angle was varied over the range:

$$15 \leq \alpha \leq 25^\circ$$

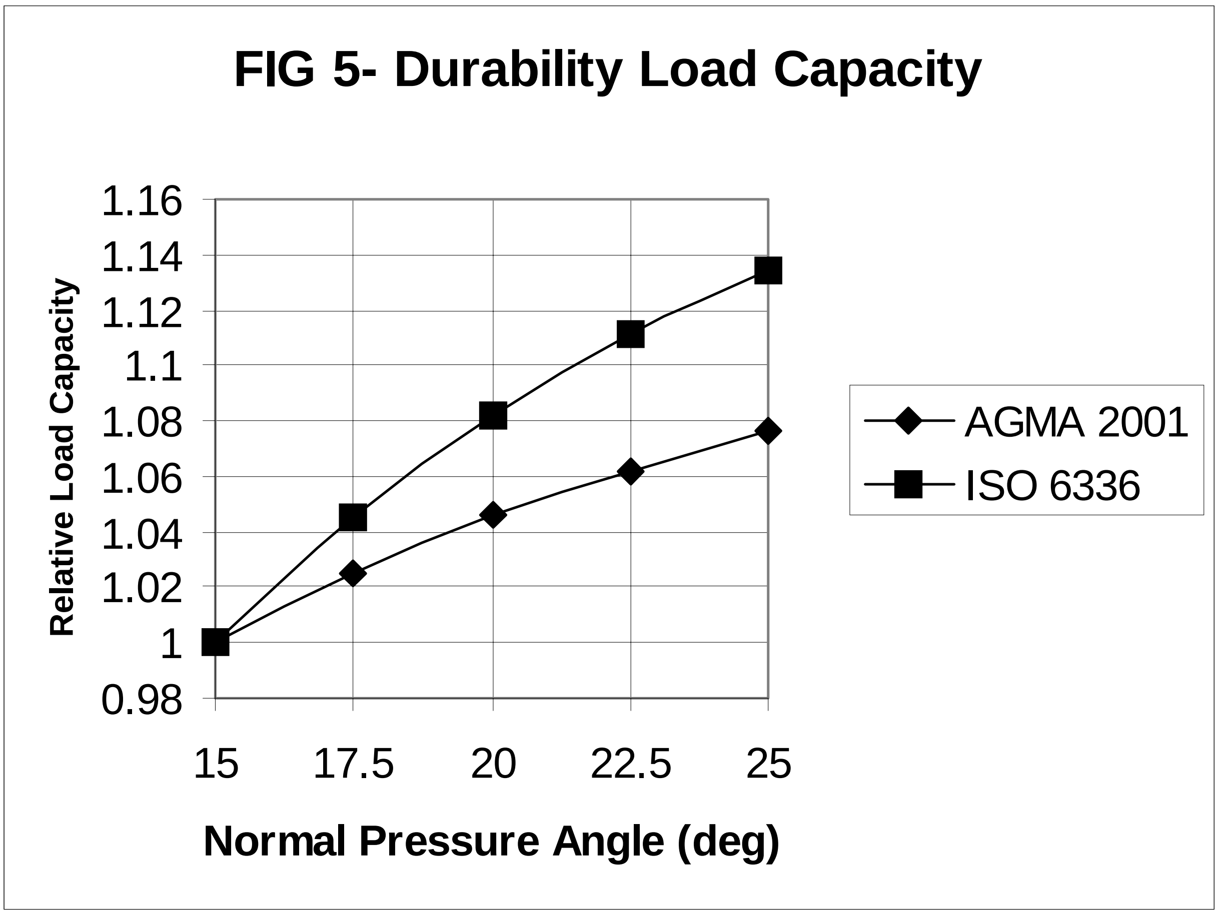

Figure 5 shows ISO 6336 durability load capacity is relatively sensitive to normal pressure angle whereas AGMA 2001 shows less response. For example, at $\alpha = 25^\circ$ the ISO load capacity increases 13% compared to $\alpha = 15^\circ$. In contrast, AGMA load capacity increases only 8%.

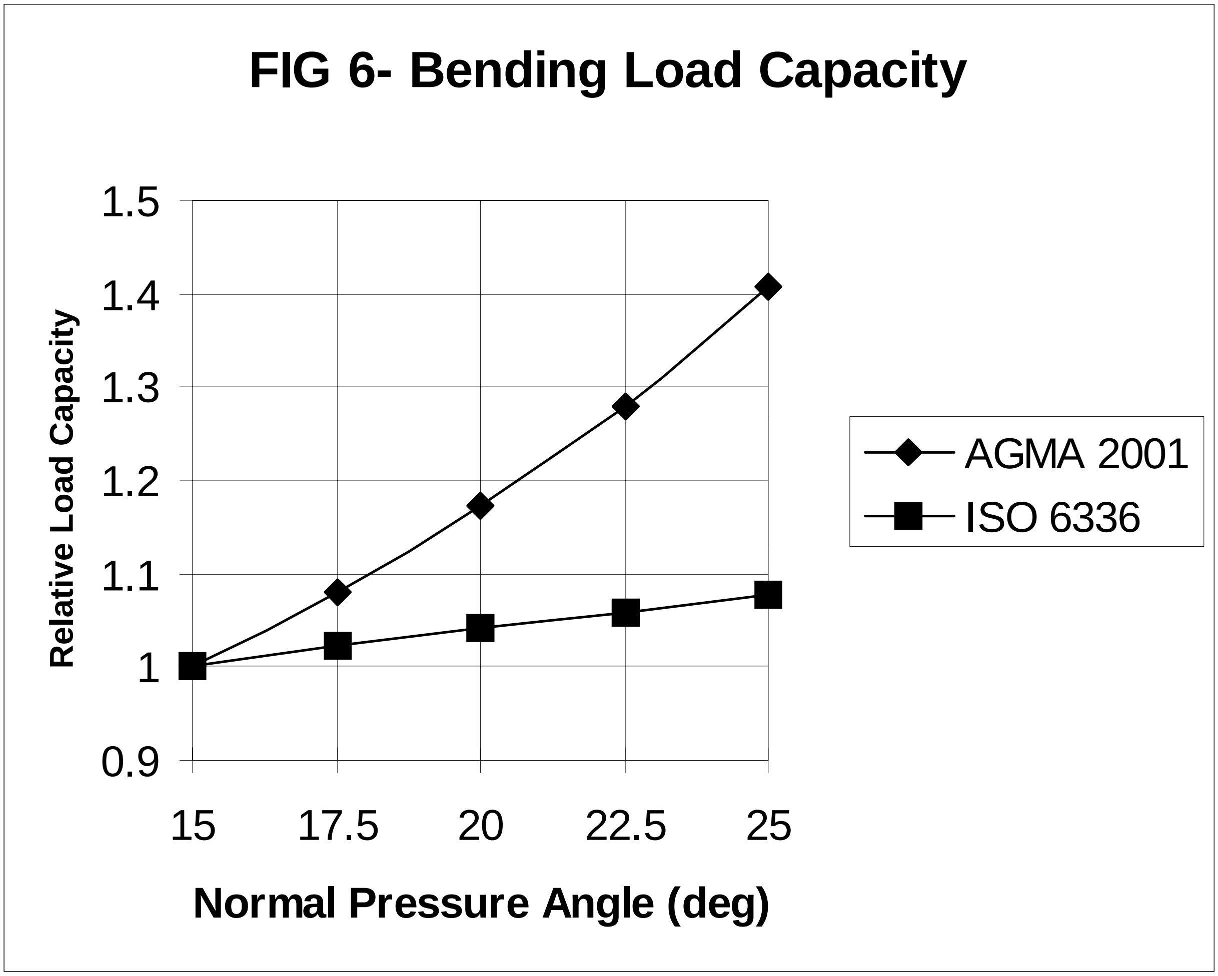

Figure 6 shows AGMA 2001 bending load capacity is very sensitive to normal pressure angle whereas ISO 6336 has negligible response. For example, at α = 25° the AGMA load capacity increases 41% compared to α = 15°. In contrast, the ISO load capacity increases only 8%.

Insensitivity of ISO 6336 bending load capacity to normal pressure angle is implausible and inconsistent with experience.

DIFFERENCES BETWEEN RATING METHODS

This study demonstrates ratings obtained with ISO 6336 and AGMA 2001 differ significantly depending on values of profile shift, helix angle, and normal pressure angle. Therefore, there are no constant factors for converting between ISO 6336 and AGMA 2001 ratings.

CONCLUSIONS

1. AGMA 2001 and ISO 6336 durability load capacities have similar response to profile shift. At x1 = 1.0 AGMA load capacity increases 42% and ISO load capacity increases 33%.

2. AGMA 2001 bending strength is very sensitive to profile shift whereas ISO 6336 has negligible response. At x1 = 1.0 AGMA load capacity increases 46%. In contrast, ISO load capacity shows a 1% <u>decrease</u> in strength. Insensitivity of ISO 6336 to profile shift, and the trend for decreasing bending strength for x1 > 0.5, are implausible and inconsistent with experience.

3. AGMA 2001 durability load capacity is very sensitive to helix angle whereas ISO 6336 has a significantly smaller response. For example, at $\beta = 7.5°$ AGMA load capacity increases 55% compared to a spur gear. In contrast, ISO load capacity shows only a 19% increase.

4. AGMA 2001 bending load capacity is very sensitive to helix angle whereas ISO 6336 has a significantly smaller response for most helix angles. Furthermore, ISO 6336 has an opposite trend for small helix angles. For example, at $\beta = 7.5°$ AGMA load capacity increases 13% compared to a spur gear. In contrast, ISO load capacity shows a 9% <u>decrease</u>. Similarly, at $\beta = 17.5°$ AGMA load capacity increases 23% whereas ISO load capacity shows only a 1% increase. For $\beta < 17°$, ISO 6336 calculates less load capacity for helical gears than spur gears. The trend for decreasing load capacity for small helix angles, and the low load capacity relative to a spur gear for $\beta < 17°$, make ISO 6336 ratings implausible and inconsistent with experience.

5. ISO 6336 durability load capacity is relatively sensitive to normal pressure angle whereas AGMA 2001 has less response. For example, at $\alpha = 25°$ ISO load capacity increases 13% compared to $\alpha = 15°$. In contrast, AGMA load capacity increases only 8%.

6. AGMA 2001 bending load capacity is very sensitive to normal pressure angle whereas ISO 6336 has a negligible response. For example, at $\alpha = 25°$ AGMA load capacity increases 41% compared to $\alpha = 15°$. In contrast, ISO load capacity increases only 8%. Insensitivity of ISO 6336 bending load capacity to normal pressure angle is implausible and inconsistent with experience.

7. Ratings obtained with ISO 6336 and AGMA 2001 differ significantly depending on values of profile shift, helix angle, and normal pressure angle. Therefore, there are no constant factors for converting between ISO 6336 and AGMA 2001 ratings.

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